

Nutrient Supply in Soilless Culture: On-Demand Strategies

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Abstract

Efficient use of nutrients is of economic and environmental importance. In soilless cultures nutrient supply is coupled to water supply. Usually, a solution with a nutrient concentration (EC) and nutrient ratios based on average uptake rates is supplied. In more sophisticated strategies this may be adapted to crop developmental stage and/or radiation levels (e.g. reduced nutrient concentration during daytime at high radiation levels). Still, drain percentages of 30-40% are common in these systems, to avoid salt accumulation in the root environment and/or shortage of some nutrient ion. A nutrient supply closer to plant demand may be obtained when supply concentration is adjusted based on continuous EC measurements in the root environment or in the drain water. In such an automated supply system the total concentration (EC) of the water supply was nearly as low as the uptake concentration, and we obtained high yields with a substantially lower drain percentage (10-20%). Obviously, such a system cannot account for variations among uptake concentration of specific nutrients. Ideally, in a recirculation nutrient solution, each ion is measured continuously in the drain, and is added in agreement with its uptake. Preferably, this uptake is anticipated by model calculations to avoid large disturbances in the nutrient supply. Recently, a large-scale project under the title 'Hydrion-line' performed a proof of principle experiment showing the possibility of controlling different macro nutrients and water delivery based on model calculations of plant growth and nutrient distribution in the substrate and on on-line measurements of plant activity and crop status (Heinen et al. 2002). This combination may lead to higher water use efficiency with a lower nutrient input, while maintaining the same production levels.

INTRODUCTION

Managing water and nutrient supply to greenhouse crops under adverse conditions, such as high electrical conductivity (EC) of water supply, requires new techniques in order to maintain high production levels and desired produce quality. Under conditions of resource constraints water loss should be minimized and nutrient emission to the surrounding environment should be abolished. In closed greenhouse systems many processes are occurring and interacting in complex ways. Many of these processes can be described by mathematical models. Processes like crop growth and metabolite allocation in relation to climatic conditions (Heuvelink, 1996; Carvalho et al., 2002) and transpiration in relation to water and nutrient uptake (De Willigen et al., 2002) can be calculated in detail based on measurements of several greenhouse parameters in combination with dynamic models. This leads to the possibility of controlling growth and development in the crop through adaptive climate control and ion specific nutrient supply (Marcelis et al., 2000). When we look at water use efficiency of horticultural produce in open field production we are horrified at the amount of fresh water wasted in production. On average a kilogram of tomatoes produced in the field will use about 200±100 liters of water. At present, in Israel this is reduced to about 60 liters per kg through drip irrigation. In Dutch greenhouses the average use is around 20 liters per kg at present. By closing the greenhouse and regaining the evaporated water it should be possible to bring this amount

down to the theoretical limit of 1.5 liter per kg tomato (see this paper). An experiment with a fully closed greenhouse system in 2002 in Naaldwijk (Wageningen-UR) revealed the possibility for this system (www.innogrow.nl) and the first greenhouse of this kind for a commercial grower is being built and will be delivered in April of this year (2004).

SUPPLY OF WATER AND NUTRIENTS IN GREENHOUSES: CURRENT PRACTICE

In soilless cultivations water and nutrients are supplied together as a nutrient solution using e.g. trickle irrigation. So-called A-B tank systems are widely used. These systems use four tanks (Gielink and Schurer, 1995), labelled A, B, Z and L. They contain respectively all the calcium salts (A tank), the phosphates and sulphates (B tank), an acid (Z tank) and a lye (L tank). Tanks A and B contain concentrated stock solutions. These solutions are mixed with the water supply to the plants, mixing rates being controlled by an EC controller. Alternatively, monosalts (liquid fertilizers) may be injected directly in the water supply circuit, so without the use of A and B tanks, as they have become commercially available in the past two years.

Management of nutrient solution supply in greenhouses involves the important questions of timing of the supply and total amount needed. Compared to cultivation in soil, the actual moments of water supply are more critical for soilless systems, as the root environment forms only a small buffer. However, high irrigation frequencies are not primarily necessary to compensate for the water use of a crop, but to prevent irreversibly drying out of the substrate (Sonneveld, 2000). This phenomenon, well-known for peat materials, also occurs in other materials like mineral wool (Van der Burg, 1990). The amount of water available in many substrate systems is at least 10 l m^{-2} , which is generally sufficient for at least one or two days. It is, therefore, not surprising that in many experiments with different water supply frequencies in substrate systems no differences in crop growth were found, provided that no exceptionally low frequencies were incorporated (reviewed by Sonneveld, 2000). The water in most of the substrates is available at low tension (Kipp and Wever, 1993) and substantial drying out of the medium in the root environment hardly increases the matrix potential (Sonneveld, 2000).

The transpiration of crops in greenhouses depends on many factors like radiation, air temperature, and humidity, leaf area, CO_2 concentration and wind speed (Stanghellini, 1987). For practical purposes, transpiration of crops can be roughly estimated, taking radiation, energy used for heating of the greenhouse, and the size of the crop into account (De Graaf, 1988). A strong correlation between radiation and transpiration has been observed. This is also shown in Fig. 1, where $1 \text{ J cm}^{-2} \text{ day}^{-1}$ extra global radiation results in 2.2 ml ($=2.2 \text{ l per m}^2$) of water needed. The driving force for transpiration and hence water uptake is the difference between water potential in the stomatal cavities and in the greenhouse air. In the stomatal cavities a relative humidity of 100% is assumed (saturated vapor pressure). As the saturating vapor pressure shows an exponential increase with temperature, the driving force for transpiration strongly increases with leaf temperature. The latter depends largely on solar radiation on the leaves.

In greenhouses, irrigation is usually automated. Growers define when the first irrigation should take place (e.g. 1 hour after sunrise), and then based on measured solar radiation following irrigation turns are defined. For example, based on the above mentioned $2.2 \text{ ml per J cm}^{-2} \text{ day}^{-1}$, one could define that after every $75 \text{ J cm}^{-2} \text{ day}^{-1}$ an irrigation turn of 2 min should take place (assuming 2 liters/dripper/h and 2.5 drippers/m^2). Often, a time limitation to the irrigation turns is implemented, e.g. no irrigation takes place after 2 h before sunset. Very accurate definition of the above mentioned settings is not necessary, as measuring the quantity of the drain water (usually collected from 6 or 8 plants placed on a special gutter) forms an excellent feedback. When the desired drain of 25-30% is not reached, apparently the radiation factor (in our example $75 \text{ J cm}^{-2} \text{ day}^{-1}$) has to be reduced or the supply in each irrigation turn (2 min in our example; 0.17 l m^{-2}) has to be increased. The rather high desired drain percentage needed to avoid salt accumulation in the root environment, shortage of a specific ion and

to account for variation between plants and drippers. Rough estimates by Marcelis et al. (2000) show that in “closed loop” greenhouse production systems approximately 120 kg N, 20 kg P and 1000 m³ water per ha are lost each year in north-western Europe, while in Mediterranean countries with no recirculation the yearly losses are approximately 300-350 kg N, 125-300 kg P and 3000-3500 m³ water per ha.

Usually, a crop-specific solution with a nutrient concentration (EC) and nutrient ratios based on average uptake rates is supplied (e.g. De Kreij et al., 1997) and frequently solution samples are taken from the root environment and analyzed in a laboratory. Based on this analysis the nutrient solution can be adjusted to the specific mutual ratios of nutrients absorbed by the crop (e.g. extra potassium). In more sophisticated strategies the nutrient solution is already on forehand adapted to crop developmental stage and/or radiation levels. For example, potassium absorption rates of a tomato crop are much higher for a crop with growing fruits compared to a vegetative crop. Furthermore, Van Ieperen (1996) showed, using an NFT system, that supply of low EC during daytime and high EC during the night (1/9) can increase tomato production compared to supplying the average EC level (5/5) during day and night.

Strategies to Separate Supply of Water and of Nutrients

An increasing body of evidence shows that uptake of water and nutrients are somehow uncoupled. Mostly this has been shown by “split-root” systems, whereby different parts of the root system are supplied by a different combination of water and nutrients (Fig. 2, Sonneveld, 2000). The main conclusion of the series of experiments conducted by Sonneveld and more recently by Mulholland et al. (2002) is that whenever osmotic potential in the root zone may be a limiting factor for water uptake, the largest absorption of water will take place in the part of the root system experiencing the most favorable osmotic potential. From Table 1, it is clear that if part of the root system experiences a high osmotic potential and another part does not, the plant as a whole does not experience the limitation (from Sonneveld, 2000).

We designed an experiment in order to show that water uptake and uptake concentration are independent of conditions in the root zone, provided stressful conditions are prevented (Stanghellini et al., 2003).

Sweet pepper *cv Spirit* were transplanted (density 4.1 m⁻²) at the beginning of January. Treatments began at the beginning of March and the experiment lasted until September 30, 2001. The control treatment was watered in a traditional fashion (resulting in a drain fraction of about 50%), whereas irrigation in the drain-less treatment aimed at maintaining volumetric water content in the rock-wool at 50% (that we had determined as a level where virtually no drain takes place). The control was based on an on-line sensor initially developed by Agrotechnology and Food Innovations, Wageningen UR (Hilhorst, 1998), and now commercially available. A built-in EC sensor was used to control salinity in the substrate. Whenever EC exceeded 3 dS/m, irrigation was drawn from a nutrient solution of 1 dS/m, as soon as EC dropped below 2.8 dS/m, then irrigation was with the “standard” solution of 3 dS/m. The same procedure applied also to the control treatment. We measured water amount given (water gift), and EC of both was measured daily. Amount and EC of drain were determined both by tipping-buckets on 6-plant sections of a row (two per treatment) and by measuring flow pumped out of an underground re-collection tank. Water uptake was determined as the difference between the two.

Daily compound nutrient uptake was determined as the difference between the sum of the products of the gift fluxes and the corresponding EC and the sum of the products of the drain events and the corresponding EC.

Plant growth and leaf area were determined by destructive measurements and yield was monitored. The mean values over the treatment period of the controlled parameters, and the total water balance. Leaf Area Index (LAI) is reported for reference for the transpiration flux.

Nutrient uptake concentration in the two sweet-pepper treatments is shown in Fig. 3 vs daily water uptake. There is significant variation among the points, which is difficult

to avoid in such “commercial scale” experiments. The main result is that the two best-fit lines are overlapping, what implies that statistically the two data sets are equal. This means that plants have taken up nutrients at the same rate, and the larger nutrient supply in the control treatment (refer to Table 2) has been wasted. This is confirmed by the fact that there is no relevant difference in water uptake, nor in fresh weight. This may be explained by the hydraulic properties of rock-wool (Da Silva et al., 1995) that display a virtually flat trend in pressure head for volumetric water contents in the range from 50 to 80%. Ignoring the large variation of the points in Fig. 3, it may be interesting to observe that the best-fit lines imply the following trend for the compound nutrient uptake concentration (dS/m):

$$C_{\text{uptake}} = 1.8 - 0.4W_{\text{uptake}}$$

with W_{uptake} in $l/(plant \cdot day)$. It is indeed well-known in practice that the uptake concentration is not constant (what would point out to a passive uptake of nutrients), but that it decreases under conditions of high potential evaporation. In other words, in such conditions the plant takes up relatively more water (necessary for maintaining turgor in spite of the transpiration) than nutrients.

Therefore, it may be useful to adapt nutrient concentration in the root zone to prevailing weather conditions. Indeed, growers are often advised to reduce concentration in the afternoon or in sunny days. This is very difficult to achieve with substrate systems, due to the high water capacity of the substrate. Of course our system (designed to maintain a constant EC in the root environment) could have been programmed to draw water from the low EC tank under given (potential transpiration) conditions, rather than in reaction to measured EC in the root environment. Instead of installing such a (rather cumbersome) two-tanks system, some Dutch growers are installing a double dripper system, one programmed to deliver fresh water (under given conditions), the other to deliver nutrient solution of a rather high EC (Fig. 4).

INTEGRATED NUTRIENT SUPPLY IN A CLOSED RECIRCULATED SYSTEM

A large scale experiment on greenhouse climate and nutrient control using plant growth and substrate diffusion models in combination with plant sensors (Marcelis et al. 2000) has recently been concluded. In a proof of principle the combined systems were used to control a tomato crop in a greenhouse for one season. The results indicate that it is possible to produce tomatoes with a diminished amount of nutrients without loss of quantity and quality. Many results have emerged from the project of which we can only mention a few here. The interaction of nitrogen and phosphorous on the plant growth has been determined (De Groot et al. 2003). Combined model based climate and nutrient control was successful (Marcelis et al. 2000, Van Straten and Gieling 2002). Plant monitoring was found to be essential to tune the basic model parameters during the season. The maximum photosynthetic capacity of the crop could vary by a factor of three in a greenhouse grown tomato crop. This is dependent on the amount of radiation received in the previous days (Van den Boogaard et al. 1999). From these and other, as yet unpublished results, it is clear that a feedback – feedforward system of combined plant sensors, plant growth and nutrient uptake models and model based climate and nutrient control systems can improve plant growth and development control in greenhouses while maintaining an extreme efficiency of resource use (Van Straten and Gieling 2002).

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Tables

Table 1. Yield and fruit weight of round tomato (cv Counter) on a split-root system whereby the two halves were supplied with nutrient solutions of the concentrations indicated (Sonneveld, 2000).

| EC value | Yield (Kg/m ²) | % | Fruit weight (g) | % |
|----------|----------------------------|-----|------------------|-----|
| 2.5/2.5 | 24.0 | 100 | 77 | 100 |
| 5.0/5.0 | 21.1 | 88 | 71 | 92 |
| 2.5/5.0 | 23.7 | 99 | 80 | 104 |

Table 2. Mean EC, both of irrigation water and in the slabs and drain. Soil volumetric water content (mean values over the treatment period). Total water fluxes and fresh weight.

| Sweet pepper | *80% | 50% | % of control |
|-----------------------------|-------|-------|--------------|
| Mean EC irrigation dS/m | 2.37 | 1.51 | 64 |
| Mean EC slab & drain dS/m | 2.9 | 2.9 | 100 |
| Volumetric water content % | 63 | 49 | 78 |
| Water gift l/plant | 344.6 | 157.1 | 46 |
| Water uptake l/plant | 143.1 | 138.6 | 97 |
| Transpiration l/plant | 136.6 | 132.2 | 97 |
| Mean LAI | 4.9 | 4.7 | 96 |
| Biomass (no roots) kg/plant | 6.5 | 6.4 | 98 |
| Yield kg/plant | 4.2 | 4.2 | 100 |

Figures

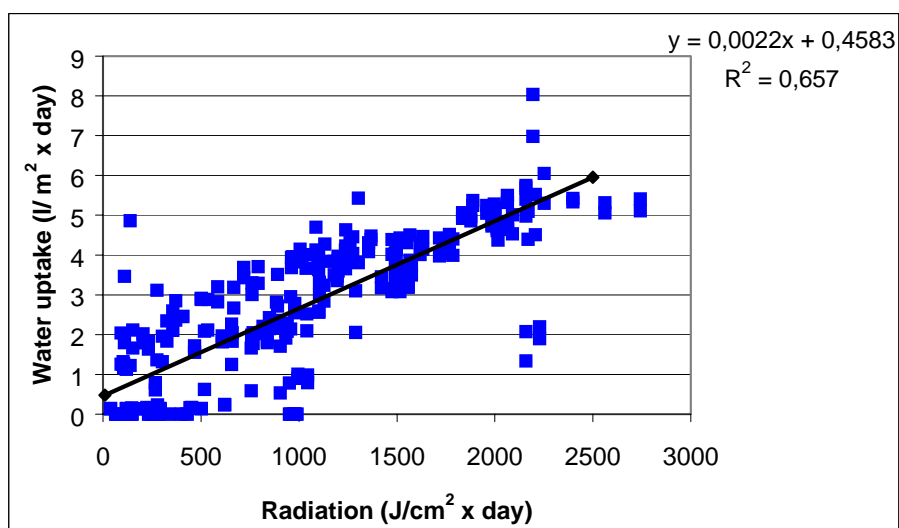


Fig. 1. Relationship between daily water uptake and global radiation outside the greenhouse, for a greenhouse cucumber crop grown from February till May.

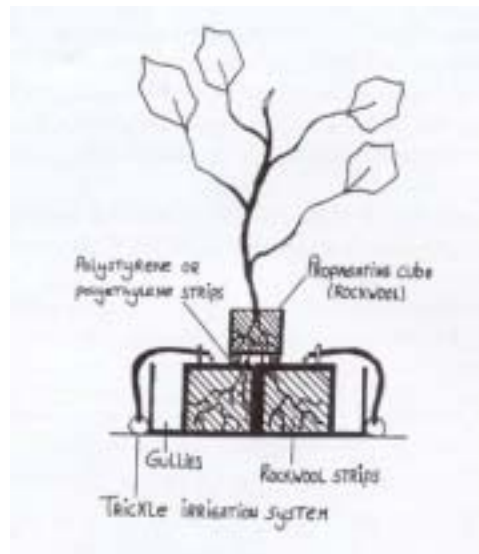


Fig. 2: Split root system by Sonneveld 2000.

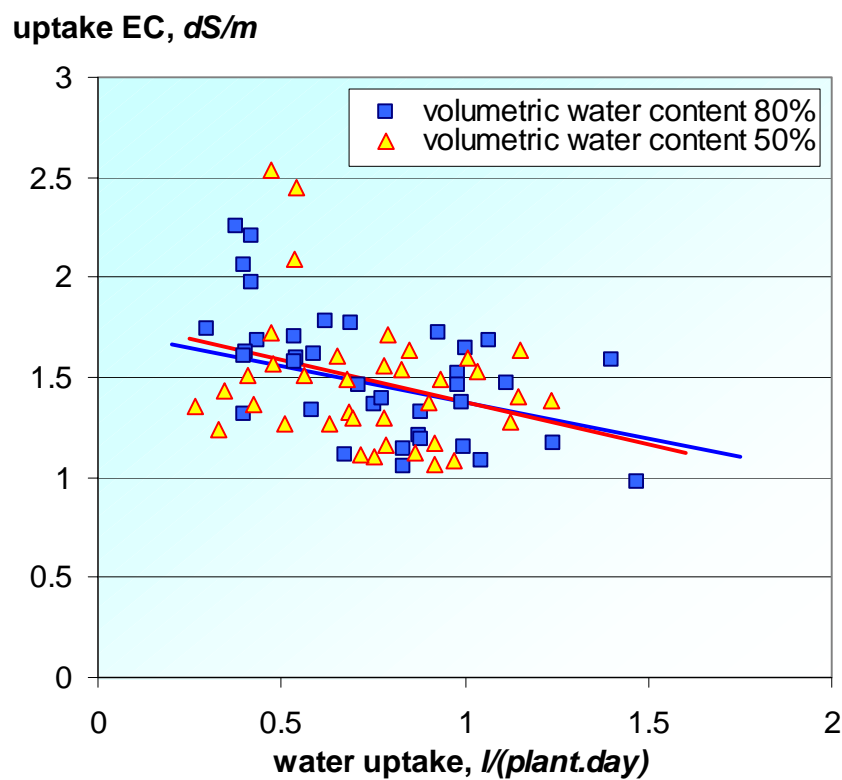


Fig. 3. Mean nutrient uptake concentration (dS/m) periods vs the water taken up in the same day. Data refer to sweet pepper subjected to the same The best-fit lines (nearly overlapping) show that there is no significant difference between uptake in the two treatments.



Fig. 4. Two dripping systems for administering low and high EC solutions.